Urban Sprawl and the Public Provision of Fire Suppression

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Abstract

Population growth in the wildland urban interface (WUI) has put a greater number of houses at risk due to wildfire while often straining the resources of fire suppression agencies and contributing to a dramatic increase in wildfire suppression expenditures. In light of these facts, this paper analyzes the consequences of the public provision of fire suppression in a monocentric city where wildfire risk is endogenously determined through the choice of where to live. Public provision leads to increased development in the WUI, higher suppression costs, and an overall decrease in welfare. Differentiated taxes based on fire risk could reduce sprawl, improve welfare and lower suppression costs.

Keywords: wildfire, wildland urban interface, fire suppression, land use, urban sprawl

JEL Classification: Q54, R14, H42, Q28

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1 Introduction

Population growth in the wildland urban interface (WUI) has put a greater number of houses at risk than ever before while often straining the resources of fire suppression agencies. The U.S. Fire Administration (2002) reports that as much as "38% of new home construction is adjacent to or intermixed with the WUI" in the western part of the U.S. At the same time, fire suppression costs have increased dramatically over the past 30 years, a cost that is ultimately passed on to taxpayers. For example, Cal Fire, the California state agency responsible for fire suppression, reports annual suppression expenditures of less than $50 million per year (in 2005 dollars) in all years for the first half of the 1980's. In contrast, expenditures were at least $120 million per year in every year for the first half of the 2000's.[1] The rise in fire suppression costs is partly a result of incentive problems in the allocation of fire suppression funds (Donovan and Brown, 2005) as well as inefficiencies within fire suppression agencies (Ingalsbee, 2000). Landowner incentive problems may also contribute to the rising costs (Amacher et al. 2006).

This paper examines a specific incentive problem, the fact that households in the WUI often receive fire suppression services for free, and examines how this incentive problem affects development in the WUI. The public provision of fire suppression may lead households to expose themselves to greater risk and thus push fire suppression costs even higher. The goal of this paper is to explain why fire suppression has traditionally been a publicly provided good and to analyze the effects of public provision when fire risk is endogenously determined by land use patterns.

Because fire suppression at one location reduces the resources available to fight fires at other locations, fire suppression is not a pure public good. However, there are several characteristics of fire suppression that inhibit the provision of the service by a private market.

[1] http://www.fire.ca.gov/fire_protection/downloads/SuppressionCostsOnepage.pdf

Fire suppression has significant positive externalities when fires are likely to spread from one location to another. Because fire departments must make quick decisions when fighting fires and cannot usually choose to suppress on a house by house basis, it is often not feasible to exclude houses in need. The non-excludability of fire suppression combined with the positive spillovers may lead to free riding and the failure of private markets.[2]

While the characteristics of fire suppression noted above may strengthen the case for public provision, there are other factors that must be considered. When fire risk is heterogeneous, the benefits of publicly provided fire suppression will accrue mostly to those at high risk. Depending on the level of risk aversion among the low risk individuals, an equal cost sharing system may leave many individuals worse off. In this case, separate fire suppression services or a risk-based cost sharing structure may make sense. This situation is exacerbated when the level of risk is endogenous, in which case individuals will expose themselves to more fire risk when they do not bear the full cost of fire suppression.

Fire needs fuel to spread and the intermix of houses and wildlands found in the WUI at the urban fringe leads to higher fire risk than traditional urban development. Thus, fire risk is not exogenous; urban development patterns determine the fire risk throughout the city. In this paper, we model wildfire risk as inversely related to household density. Whereas an urban fire will originate at one location and spreads from structure to structure, a wildfire may threaten many homes at once and often spreads even when structures are successfully defended. The ability of fires to spread even as structures are saved occurs due to low density development interspersed with vegetation that fuels the fire. Hence, low density development is a key ingredient in the increased fire risk for WUI homes compared to traditional urban homes.[3]

[2]Even in the absence of free riding, the public provision of fire suppression may make sense as a form of risk pooling or insurance. By buying into fire suppression whether or not a homeowner experiences a fire, they insure against the high costs of fire suppression when the service is needed.

[3]Syphard et al. (2007) actually argue that the relationship between density and the frequency of fires is an inverted U with the frequency of fires increasing as density decreases until some point where it begins to decrease. However, the range of densities over which fires are increasingly related to density is small enough

Previous work on the economics of fire suppression has focused on fire suppresion agency management and the factors affecting fire suppression costs (Duncombe and Yinger 1993; Donahue 2004; Prestemon and Donovan 2008; Yoder and Gebert 2012) as well as tradeoffs between mitigation and suppression (Amacher et al. 2006; Mercer et al. 2008; Crowley et al. 2009). Amacher et al. (2006) and Crowley et al. (2009), in particular, are similar to this paper in their investigation of the consequences of publicly provided fire suppression. Their context is on rural land and the effect of public provision on the incentives to invest in fire risk mitigation. This paper will instead look at how land use in urban areas depends on fire suppression management decisions and how the pattern of growth and development in the western U.S. may be tied to decisions about fire suppression funding.

The approach of this paper is based on the monocentricy city model (Alonso 1964; Mills 1967; Muth 1969). Frame (1998) and Frame (2001) also use the monocentric city framework to study how risks from natural hazards and disasters affect city structure. Frame (2001) shows that subsidization of insurance for those in high risk areas (such as the flood plain) can make everyone better off, a result that is intuititvely different from the findings of this paper. The primary difference from this paper is that the risk in Frame (2001) is exogenous and the benefits from subsidization reflect lower aggregate transportation costs. Other papers that have used the monocentric city framework to examine the effect of government taxes and expenditures on city structure include Su and DeSalvo (2008), Brueckner (2005), and Borck and Wrede (2005).

The paper proceeds as follows. Section 2 provides some additional information about fire suppression to further motivate the analysis in this paper. Section 3 extends the classic monocentric city model to include fire suppression expenditures and fire damages. Section 4 presents results for an "urban fire" in which fire risk is exogenous and a "wildfire" in which fire risk is inversely related to urban density. Public provision of fire suppression funded

that they would not be considered part of an urban area.

through income taxation makes residents better off for urban fires but has an ambiguous impact for wildfires where it also leads to excessive urban sprawl. Section 5 proposes a risk-based tax as a means of funding public fire suppression that is superior to both private provision and public provision with income taxation. Section 6 concludes with some policy implications and a discussion of alternative approaches to fire suppression that will lead to higher welfare and less sprawl.

2 Background on Fire Suppression

In 18th and 19th century America, fire suppression was typically in the hands of volunteer fire fighting companies. Funding for these companies came from a variety of sources including insurance companies and local governments. In both cases, a "fee-for-service" system was common in which the fire fighting company would be rewarded with a payment for successfully putting out a fire. Insurance companies would mark buildings that they had insured so that fire fighting companies would know they would receive payment for protecting the building (Zurier, 1982, p 30). In many cities, there were multiple fire fighting companies, and the first to arrive at the scene of a fire would be the one paid or the one to receive the highest reward. This led to intense competition among companies to be the first to arrive at a fire. In some notable cases, buildings were "left to burn while opposing companies fought with each other" for the opportunity to put out the fire and receive payment (Zurier, 1982, p. 74). Partially in response to increasing violence associated with private fire fighting companies and the first-to-fire payment policy, the late 19th century saw a shift to public provision of fire suppression services in many cities, starting with Cincinatti in 1853.

Although there were other solutions to the problems of violence arising from fire suppression markets in early America, one clear reason why public provision has persisted into modern times is the positive externality from successful suppression. Private provision would raise concerns that overall fire suppression would be too low. For example, individual homeowners may find it prohibitively expensive to fight a fire but a coalition of neighboring homeowners might jointly find it worth it.

The middle of the twentieth century saw rapid growth for many cities in the Western U.S., the expansion of cities into wildland areas, and the emergence of the WUI. What had once been two separate issues, urban fire suppression and wildland fire management, merged into a joint problem requiring new solutions that balanced the needs of the natural ecosystem with those of property owners in the expanding city. As an example, Pyne et al. (1996, p. 298, 718) describe the changing landscape in the Los Angeles area following World War II:

> The exploding population thrust into and around the mountains, pushing with mounting force against forest, park, and reservoir reserves. To aging chaparral fuels the new era added houses, often outfitted with highly flammable wooden roofs, and to the old cycle of ignitions it added futher sources from powerlines, machinery, children, and arsonists. Conflagarations that had formerly raged in the backcountry or along a tattered rural fringe now, by virtue of this instant geography, burned into suburbs...
>
> The real fire problem was structural, the way in which the urban intermixed with the wild, the reluctance to build suitable houses and trim decadent brush, the refusal to design for fire hazards in land use planning...

As noted above, fire suppression costs have increased dramatically in recent years. One of the biggest contributors to the increasing costs is the growth of development in the WUI and the decreasing density of American cities. A recent report from the Department of Agriculture indicates that over half of all fire fighting expenditures are related to defending homes in the WUI (USDA Office of the Inspector General, 2006). Growth in the WUI contributes to increasing fire suppression costs for two reasons. As new developments form on the outskirts of urban areas, more homes are in high risk areas that require the services of fire fighters. Equally important is that fire suppression agencies have changed the way they fight fires in response to development in the WUI. Inglasbee (2010) notes that "Focusing suppression resources on the WUI removes options from firefighters to locate themselves in the best places for taking the safest, most efficient and effective actions."

It is widely accepted that protecting structures (most of which are privately owned) is the most important goal of fire suppression agencies once everyone is evacuated and lives are not at stake (Inglasbee, 2010). Pyne et al. (1996, p. 469) note that "Ethical instincts and legal strictures have argued for the preferential protection of dwellings even if this mean that the overall fire continues to propagate freely." However, the cheapest way to contain a fire and protect a nearby urban area is often not the same as the way that minimizes loss of structures. Firefighters would like to use "existing forest roads, ridges, or rivers to anchor firelines," but protecting homes in the WUI is often not compatible with using these features (Inglasbee, 2010). In extreme cases, the cost of fire suppression sometimes even exceeds the value of the structure being defended (Inglasbee, 2010).

Containment of a wildfire and protection of the central city closely resembles a pure public good. It is not feasible to protect individual structures in the central city from a wildfire without protecting all (non-excludability) and there is no additional cost to protect one more structure in the central city (non-rivalry). Fire suppression in the WUI cannot be viewed in the same way. As noted above, there are significant additional resources used by fire suppression agencies to protect homes in the WUI (rivalry) and it is possible to contain a fire without saving some specific structures in the WUI (excludability). In some cases, saving a structure is complementary to containing the fire, but often times it is not. Since defending the WUI more closely resembles a private good, it brings into question whether public provision is a good policy. While there are clear positive externalities related to structure defense, it is less clear that public provision is a welfare-improving policy to deal with these externalities.

To summarize the key facts that motivate this paper, there has been tremendous growth in the WUI in the past 30 years. At the same time, there has been a dramatic increase in fire suppression costs that is directly related to fighting fires in the WUI. Homeowners in the WUI typically do not pay more for fire suppression than other homeowners. Taking these points together, a large portion of the benefits of public provision of fire suppression accrue to homeowners in the WUI while the increasing cost of suppression is an expense borne by the taxpayers. There are different approaches to fighting fires. One approach is to contain fires at minimum cost once everyone is evacuated. A different approach is to minimize loss of structures at any cost. Current fire suppression uses the latter approach. This is important because it illustrates that the high cost of fire suppression is not an inevitable consequence of development in the WUI but a policy choice. The point of this paper is to examine some of the land use consequences arising from this policy in the context of an urban economic model.

3 The Model

The model is based on the classic monocentric city model from Alonso (1964), Mills (1967), and Muth (1969), modified to allow for the possibility of damages due to wildfire. We model the decisions of consumers in a closed linear city with population n who all work in the Central Business District (CBD) located at $x = 0$. The residential sector of the city includes locations along a line of unit width extending from $x = 0$ to $x = \bar{x}$. At locations $x > \bar{x}$, land is used for agriculture and earns an exogneously determined land rent r_a. Assume that consumers derive utility from consumption of land l and a numeraire good z, $U = U(z, l)$, and that U is continuous, increasing in both goods, and quasi-concave. Further, assume that agents are risk neutral with respect to uncertainty in their final consumption of z that stems from possible fire damages.[4] This assumption effectively means that we can use expected fire damages in the budget constraint when maximizing utility.

Assume that fires occur according to a Poisson process such that the probability of m fires occurring in the city is given by a Poisson distribution with parameter λ and the expected number of fires is equal to λ. Assume that the location at which any fire originates is random and independent of the location of other fires. When a fire occurs, assume it originates at a fixed distance from the city center and that it initially threatens all homes at that distance.

Once a fire initiates at some random location, the residents at that location immediately engage in fire suppression. Fire suppression has two effects. First, it reduces damages at the location of the fire. This is the direct benefit of fire suppression that residents will take into account when choosing the extent of their fire suppression activities. Second, fire suppression reduces the likelihood that the fire spreads to other locations. This benefit is a positive externality to fire suppression, benefitting other residents but without any benefit to the residents engaged in the suppression. If the fire does spread to one or more other locations, this process repeats - residents at the other locations threatened by the fire engage in fire suppression that reduces their damages as well as the further spread of the fire through the city. Thus, a single fire that initiates at one random location can ultimately threaten many locations in the city depending on the effectiveness of fire suppression.

Conditional on a fire threatening a home, a resident chooses a level of fire suppression $c \in [0, \overline{c}]$ where the price of one unit of c is normalized to 1. The losses incurred by the resident are a random variable $S \in [0, \overline{S}]$ with distribution $F(S; c)$ which depends on the resident's fire suppression c such that $\forall c_1, c_2$ where $c_1 > c_2$, $F(S; c_1) \geq F(S; c_2)$ $\forall S$ and $\exists S$ such that $F(S; c_1) > F(S; c_2)$. Assume this distribution is identical for all locations in the city. Let $\hat{S}(c) = \int_0^{\overline{S}} S dF(S; c)$ denote the expected value of S as a function of c. Based on

[4]Formally, this means that agents maximize expected utility but have a utility function such that, if $\gamma \in [0, \overline{\gamma}]$ represents a random shock to z with PDF $g(\gamma)$, then $\int_0^{\overline{\gamma}} U(z - \gamma, l) g(\gamma) d\gamma = U(z - \hat{\gamma}, l)$ where $\hat{\gamma} = \int_0^{\overline{\gamma}} \gamma g(\gamma) d\gamma$.

the above assumption regarding $F(S;c)$, note that $\frac{d\hat{S}}{dc} < 0$. Further assume that $\frac{d^2\hat{S}}{dc^2} > 0$.

If fire suppression is privately provided, then both the cost of fire suppression and the damages from a fire reduce an individual's consumption of other goods. At the time that a fire occurs, an individual chooses the level of c that minimizes the expected cost of the fire. Let c^* denote an individual's optimal choice of fire suppression which satisfies $\frac{d\hat{S}}{dc} = -1$.[5] Given the assumption that the distribution F is equivalent at all locations, residents at all locations will choose the same c^*.

In addition to reducing damages due to fire, fire suppression also reduces the spread of the fire to other locations in the city, although individuals will not consider these suppression externalities when choosing their level of suppression c^*. Conditional on the occurrence of a fire, but before the location of the fire is known, the probability that the fire reaches a location x is a function of the fire suppression at every location in the city as well as the density at location x. Let $\Pi(c, l(x))$ denote the probability that a fire reaches a given property as a function of the city-wide level of fire suppression c and density $D \equiv \frac{1}{l(x)}$. The expected number of fires to reach a property is thus $\lambda\Pi(c, l(x))$. We assume that $\frac{\partial\Pi}{\partial c} \leq 0$ and $\frac{\partial\Pi}{\partial l} \geq 0$. First, fire suppression at all locations in the city affects the probability of a fire at any location because fire suppression reduces the spread of fires from one location to another. The specific topography of a city determines the likelihood of a fire spreading between any two locations. In the interest of parsimony, we assume symmetric fire suppression externalities which allows us to focus on the case where the level of fire suppression is equivalent at all locations in the city. Second, wildfire risk is inversely related to household density (Syphard et al., 2007). This is the key feature of the model - that wildfire risk is endogenously determined by urban development patterns. This feature is motivated by the earlier discussion of the link between wildfire risk and low density development in the WUI.

[5]We assume that the choice of c that minimizes private fire costs is not the maximal level of suppression, i.e. $c^* < \bar{c}$.

If individuals are risk neutral and privately pay for their personal suppression costs, then their budget constraint includes the expected costs of fire, made up of two parts, the cost of suppression and actual damages. Let c^p denote the level of suppression in which case expected damages are $\hat{S}(c^p)$. Then, the budget constaint is $y = z + tx + rl + \lambda\Pi(c^p, l)(c^p + \hat{S}(c^p))$ where y is household income, t is the annual commuting cost per unit travelled, and r is land rent. Note that, if residents are free to choose whatever level of suppression they want, they will choose $c^p = c^*$, but we leave open the possibility of other values of c^p such as government suppression mandates that will be considered in the next section.

If fire suppression is publicly provided, then an individual pays the (lump sum) income tax τ and, in the event of a fire, the individual may incur damages but does not bear the cost of fire suppression.[6] In this case, the level of fire suppression at any location c^g is set by the government providing the suppression. The budget constraint in this case is: $y = z + tx + rl + \tau + \lambda\Pi(c^g, l)\hat{S}(c^g)$. τ is set to balance the government budget:

$$\tau = \frac{1}{n}\int_0^{\overline{x}} \frac{1}{l(x)}\lambda\Pi(c^g, l(x))c^g dx \tag{1}$$

Suppose that, at the time when individuals make their housing decisions (before any fires occur), individuals are unsure whether fire suppression will be publicly or privately provided with δ representing the probability (known to everyone) that suppression is publicly provided. Thus, $\delta = 0$ represents the case where fire suppression is privately provided for sure and $\delta = 1$ represents the case where fire suppression is publicly provided for sure. The purpose of the parameter δ is to generate comparative statics that demonstrate the effect of a change from private to public provision. A risk neutral individual therefore faces the following general budget constraint:

[6]A lump sum income tax is a reasonable way to incorporate fire suppression funding into our model. In California, for example, Cal Fire's primary source of funding is the state General Fund which is itself primarily funded by income taxes.

$$y = z + tx + rl + \delta\left(\tau + \lambda\Pi(c^g, l)\hat{S}(c^g)\right) + (1-\delta)\lambda\Pi(c^p, l)(c^p + \hat{S}(c^p)) \quad (2)$$

Although the inclusion of fire damages and the introduction of the parameter δ distinguish the budget contstraint from that in traditional urban models, the other aspects of the model are conventional for a monocentric city. The budget constraint leads to the following utility maximization problem:

$$max_l U(y - tx - rl - \delta\left(\tau + \lambda\Pi(c^g, l)\hat{S}(c^g)\right) - (1-\delta)\lambda\Pi(c^p, l)(c^p + \hat{S}(c^p)), l). \quad (3)$$

The first order condition for a maximum is:

$$\frac{U_1(z,l)}{U_2(z,l)} = r + \delta\lambda\frac{\partial\Pi}{\partial l}\hat{S}(c^g) - \delta\lambda\frac{\partial\Pi}{\partial l}(c^p + \hat{S}(c^p)) \quad (4)$$

At the urban equilibrium, residents at all locations achieve the same utility level u, leading to the following condition:

$$U(y - tx - rl - \delta\left(\tau + \lambda\Pi(c^g, l)\hat{S}(c^g)\right) - (1-\delta)\lambda\Pi(c^p, l)(c^p + \hat{S}(c^p)), l) = u \quad (5)$$

Our method of solving the model follows that in Wheaton (1972) and Brueckner (1987). Equations 4 and 5 are solved simultaneously to yield the optimal choice of l and the equilibrium land rent r in terms of x, y, t, δ, λ, c^g, c^p, u, and τ:

$$l^* = l(x, y, t, \delta, \lambda, c^g, c^p, u, \tau)$$

$$r^* = r(x, y, t, \delta, \lambda, c^g, c^p, u, \tau)$$

By differentiating Equation 5 with respect to x, u, δ, and τ, we derive the following results on the function r that will be used in the later sections:

$$\frac{\partial r}{\partial x} = \frac{-t}{l} < 0 \tag{6}$$

$$\frac{\partial r}{\partial u} = \frac{-1}{U_1(z,l)l} < 0 \tag{7}$$

$$\frac{\partial r}{\partial \delta} = \frac{\lambda \Pi(c^p, l)(c^p + \hat{S}(c^p)) - \tau - \lambda \Pi(c^g, l)\hat{S}(c^g)}{l} \tag{8}$$

$$\frac{\partial r}{\partial \tau} = -\frac{\delta}{l} \leq 0 \tag{9}$$

To complete the model, we state two additional conditions that are standard for a monocentric city. Equation 10 imposes that urban land rent at the city boundary exactly equals the agricultural land rent r^a.

$$r(\overline{x}, y, t, \delta, \lambda, c^g, c^p, u, \tau) = r^a \tag{10}$$

Equation 11 imposes that the population n fits in the city since $\frac{1}{l(x)}$ is the population density at any location x and the linear city extends from location 0 to $\overline{x}$ with unit width.

$$n = \int_0^{\overline{x}} \frac{1}{l(x)} dx \tag{11}$$

Equations 1, 10, and 11 are solved simultaneously for the endgoenous variables u, $\overline{x}$, and τ.

4 Results

We divide the analysis into two cases, a city that experiences urban fires but not wildfires and a city that experiences both urban fires and wildfires. We first consider the case of a city that does not experience wildfires. In the context of the model, this means that fire risk does not depend on density, or $\frac{\partial \Pi}{\partial l} = 0$. We will show that public provision of fire suppression improves the welfare of city residents. This is a result of the positive spillovers associated with fire suppression (from reducing the spread of fires) and the fact that private provision will lead to under-investment in fire suppression from a failure to internalize the positive suppression externalities. The correction of the market failure due to positive suppression externalities is the likely reason why public provision of fire suppression is the most common way of providing fire suppression services today.

The second part of this section will consider the case of a city that faces wildfire risk that depends on urban density. We will show that public provision funded by an income tax leads to excessive urban sprawl and may have a positive or negative effect on the welfare of residents relative to private provision. The following section will further show how alternate means of funding fire suppression can lead to less sprawl than with an income tax and to welfare improvements relative to both private provision and public provision with income taxation .

4.1 Urban Fire Risk

In this section, we consider urban fires where density does not affect fire risk, and so $\Pi(c, l) = \Pi^c(c)$. Equation 1 can then be simplified to:

$$\tau = \frac{\lambda \Pi^c(c) c^g}{n} \int_0^{\overline{x}} \frac{1}{l(x)} dx = \lambda \Pi^c(c) c^g \tag{12}$$

Let $\Omega(c)$ denote the expected cost of fire in the entire city as a function of c:

$$\Omega(c) = \int_0^{\overline{x}} \frac{1}{l(x)} \lambda \Pi^c(c)(c + \hat{S}(c))dx = n\lambda \Pi^c(c)(c + \hat{S}(c))$$

With private provision, once a fire reaches a property, residents choose the level of fire suppression that minimizes the sum of suppression costs and expected fire damages. This balances the marginal cost of suppression against the benefit in terms of reduced expected damages from fire. This level of fire suppression c^* is sub-optimal because it ignores the benefits of suppression related to a reduction in the spread of the fire to other locations. This additional benefit of suppression shows up in the dependency of Π on the city-wide level of suppression. The optimal level of suppression minimizes the sum of suppression costs and expected fire damages in the entire city. Let c^o denote the optimal level of suppression that minimizes $\Omega(c)$. Since $\Omega(c)$ is strictly decreasing for all $c \in [0, c^*]$, $c^o > c^*$.

With public provision, the government chooses a constant level of suppression c^g at all locations. Then, let $\Pi^g = \Pi^c(c^g)$ denote the probability of any fire reaching any given location (given c^g).

The following proposition demonstrates that public provision can lead to an increase in welfare relative to private provision if the level of suppression chosen by the government corrects the under-provision of private suppression due to suppression externalities.

Proposition 4.1. $\forall c^g \in [0, \overline{c}]$, *the following statements are true if and only if* $\Omega(c^g) < \Omega(c^*)$*:*

1. *all residents of the city are better off with public provision of* c^g *than with private provision, and*

2. *the city is spatially larger with public provision of* c^g *than with private provision.*

Proof. Let $\hat{y} = y - \delta \left(\tau + \lambda \Pi^g \hat{S}(c^g)\right) - (1-\delta)\lambda \Pi^c(c^*)(c^* + S^*)$ denote the expected disposable income after paying all costs related to fire suppression and assuming residents choose $c^p = c^*$. Substituting Equation 12, $\hat{y} = y - \delta\lambda\Pi^g(c^g + \hat{S}(c^g) - (1-\delta)\lambda\Pi^c(c^*)(c^* + S^*)$. If $\Omega(c^g) < \Omega(c^*)$, then an increase in δ (i.e. a switch from private provision to public provision) is equivalent to an increase in $\hat{y}$. We can then use established results from Fujita (1989) to prove our results. Fujita (1989) shows that an increase in household income causes equilibrium utility to increase ($\frac{du}{d\hat{y}} > 0$) and the city to grow spatially larger ($\frac{d\overline{x}}{d\hat{y}} > 0$). These results imply that residents are better off with public provision of c^g than private provision ($\frac{\partial u}{\partial \delta} > 0$) and that the city is spatially larger with public provision that private provision ($\frac{\partial \overline{x}}{\partial \delta} > 0$).

If $\Omega(c^g) > \Omega(c^*)$, then an increase in δ (i.e. a switch from private provision to public provision) is equivalent to a decrease in $\hat{y}$ and both results from the previous paragraph are reversed.

If $\Omega(c^g) = \Omega(c^*)$, then an increase in δ (i.e. a switch from private provision to public provision) has no effect on $\hat{y}$ and no effect on the city in general (i.e. equilibrium utility and the city boundary are equivalent with private and public provision). □

Based on this proposition, we can reach two important conclusions. First, public provision of c^o makes everyone in the city better off than private provision since c^o minimizes $\Omega(c)$ by definition. Second, although public provision can make residents better off, this depends on the choice of c^g such that $\Omega(c^g) < \Omega(c^*)$. c^g must be set above c^* to correct the externality. Furthermore, it may be possible to have too much suppression if the costs of suppression outweigh the benefits of lower fire damage. For example, if $\Omega(\overline{c}) > \Omega(c^*)$, then public provision of $\overline{c}$ makes residents worse off than private provision because too many resources are dedicated to fire suppression that would be better spent on consumption of the numeraire.

Public provision in this context leads to sprawl since the city grows and becomes less dense in response to an increase in δ. This sprawl is justified since individuals have additional disposable income as a result of the reduction in the costs of fire and may choose to spend that additional income on more land, leading to a lower density city but making everyone better off.

The purpose of this section has been to justify the public provision of fire suppression as a way to correct the market failure that would occur with private provision due to positive fire suppression externalities. Under the assumption that pre-suppression fire risk is exogenous, public provision can make everyone better off if the level of suppression leads to lower overall fire costs (suppression cost plus fire damage) than private provision would.

4.2 Wildfire Risk

In this section, we turn to the case of wildfire risk where low density development leads to increased fire risk. Here we assume that $\frac{\partial \Pi}{\partial l} > 0$ since urban density $D(x) \equiv \frac{1}{l(x)}$. In the interest of parsimony, we further assume that the effects of c and D are separable in Π and that Π is inversely related to density and therefore linear in land choice l.

$$\Pi(c, l) = \Pi^c(c) l \tag{13}$$

The following proposition leaves open whether public provision is better or worse than private provision in general but instead shows that a private mandate to choose c' is always better than public provision of c'. Intuitively, the private mandate is better because public provision leads to sprawl, increasing the overall fire risk in the city and leading to higher expected fire costs.

Proposition 4.2. $\forall c' \in [0, \bar{c}]$, *public provision of* c'*, compared to a mandate that all residents privately purchase* c'*:*

1. *all residents of the city are worse off with public provision than with a private mandate, and*
2. *the city is spatially larger with public provision than with a private mandate.*

Proof. Since we are comparing private vs. public provision of the same level of suppression, we let $c^g = c^p = c'$. We show that $\frac{\partial u}{\partial \delta} < 0$ (public provision makes residents worse off) and

$\frac{\partial \overline{x}}{\partial \delta} > 0$ (public provision makes the city grow spatially). Noting that $\frac{\partial r}{\partial x} = \frac{-t}{l}$, Equation 11 can be written as

$$tn = -\int_0^{\overline{x}} \frac{\partial r}{\partial x} dx = r(0) - r(\overline{x})$$

Applying Equation 10 yields

$$tn = -\int_0^{\overline{x}} \frac{\partial r}{\partial x} dx = r(0) - r^a$$

Totally differentiating with respect to δ yields

$$0 = \frac{\partial r(0)}{\partial \delta} + \frac{\partial r(0)}{\partial u}\frac{\partial u}{\partial \delta} + \frac{\partial r(0)}{\partial \tau}\frac{\partial \tau}{\partial \delta}$$

or

$$\frac{\partial u}{\partial \delta} = -\frac{\frac{\partial r(0)}{\partial \delta} + \frac{\partial r(0)}{\partial \tau}\frac{\partial \tau}{\partial \delta}}{\frac{\partial r(0)}{\partial u}} \tag{14}$$

From Equation 7, we know that $\frac{\partial r(0)}{\partial u} < 0$ so $\frac{\partial u}{\partial \delta}$ has the same sign as $\frac{\partial r(0)}{\partial \delta} + \frac{\partial r(0)}{\partial \tau}\frac{\partial \tau}{\partial \delta}$. Because $c^g = c^p = c'$, $\hat{S}(c^g) = \hat{S}(c^p) = \hat{S}(c')$ and

$$\frac{\partial r}{\partial \delta} = \frac{\lambda \Pi^c(c') l c' - \tau}{l}$$

Because τ is the total expected suppression cost per person averaged across the whole city and $\lambda \Pi^c(c') l(x) c'$ is the expected cost of suppression for a person at location x and because the optimal choice of l is increasing with x ($\frac{\partial l}{\partial x} > 0$), we know that $\lambda \Pi^c(c') l(0) c' - \tau < 0$ and therefore,

$$\frac{\partial r(0)}{\partial \delta} = \frac{\lambda \Pi^c(c') l(0) c' - \tau}{l(0)} < 0 \tag{15}$$

Using this and the fact that $\frac{\partial r}{\partial \tau} \leq 0$ implies that, if $\frac{\partial \tau}{\partial \delta} > 0$, then $\frac{\partial u}{\partial \delta} < 0$.

Totally differentiating Equation 1 with respect to δ yields

$$\frac{\partial \tau}{\partial \delta} = \frac{c' \Pi^c(c')}{n} \frac{\partial \overline{x}}{\partial \delta} \tag{16}$$

which implies that $\frac{\partial \tau}{\partial \delta}$ and $\frac{\partial \overline{x}}{\partial \delta}$ have the same sign.

Totally differentiating Equation 10 with respect to δ yields

$$\frac{\partial r(\overline{x})}{\partial \delta} + \frac{\partial r(\overline{x})}{\partial u}\frac{\partial u}{\partial \delta} + \frac{\partial r(\overline{x})}{\partial \tau}\frac{\partial \tau}{\partial \delta} + \frac{\partial r(\overline{x})}{\partial x}\frac{\partial \overline{x}}{\partial \delta} = 0$$

Rearranging and substituting Equation 14,

$$\frac{\partial r(0)}{\partial u}\frac{\partial r(\overline{x})}{\partial x}\frac{\partial \overline{x}}{\partial \delta} = \frac{\partial r(\overline{x})}{\partial u}\left[\frac{\partial r(0)}{\partial \delta} + \frac{\partial r(0)}{\partial \tau}\frac{\partial \tau}{\partial \delta}\right] - \frac{\partial r(\overline{x})}{\partial \delta}\frac{\partial r(0)}{\partial u} - \frac{\partial r(\overline{x})}{\partial \tau}\frac{\partial \tau}{\partial \delta}\frac{\partial r(0)}{\partial u}$$

Since $\frac{\partial r(0)}{\partial u} < 0$ and $\frac{\partial r(\overline{x})}{\partial x} < 0$, $\frac{\partial \overline{x}}{\partial \delta}$ has the same sign as

$$\frac{\partial r(\overline{x})}{\partial u}\left[\frac{\partial r(0)}{\partial \delta} + \frac{\partial r(0)}{\partial \tau}\frac{\partial \tau}{\partial \delta}\right] - \frac{\partial r(\overline{x})}{\partial \delta}\frac{\partial r(0)}{\partial u} - \frac{\partial r(\overline{x})}{\partial \tau}\frac{\partial \tau}{\partial \delta}\frac{\partial r(0)}{\partial u} \tag{17}$$

Rearranging 17 yields

$$\frac{\partial \tau}{\partial \delta}\left[\frac{\partial r(\overline{x})}{\partial u}\frac{\partial r(0)}{\partial \tau} - \frac{\partial r(0)}{\partial u}\frac{\partial r(\overline{x})}{\partial \tau}\right] + \frac{\partial r(\overline{x})}{\partial u}\frac{\partial r(0)}{\partial \delta} - \frac{\partial r(\overline{x})}{\partial \delta}\frac{\partial r(0)}{\partial u} \tag{18}$$

Substituting Equations 7, 8 and 9, 18 becomes

$$\frac{\partial \tau}{\partial \delta}\frac{\delta}{l(0)l(\overline{x})}\left[\frac{1}{U_1(z(\overline{x}), l(\overline{x}))} - \frac{1}{U_1(z(0), l(0))}\right] + \frac{1}{l(0)l(\overline{x})}\left[\frac{\lambda \Pi^c l(\overline{x})c' - \tau}{U_1(z(0), l(0))} - \frac{\lambda \Pi^c l(0)c' - \tau}{U_1(z(\overline{x}), l(\overline{x}))}\right] \tag{19}$$

Since $\frac{dU_1(z(x),l(x))}{dx} > 0$, the term multiplied by $\frac{\partial \tau}{\partial \delta}$ is negative. Combining that with the fact that $\frac{\partial \tau}{\partial \delta}$ and $\frac{\partial \overline{x}}{\partial \delta}$ have the same sign (Equation 16), we conclude that that sign is the same as the second term in 19:

$$\frac{1}{l(0)l(\overline{x})}\left[\frac{\lambda \Pi^c l(\overline{x})c' - \tau}{U_1(z(0), l(0))} - \frac{\lambda \Pi^c l(0)c' - \tau}{U_1(z(\overline{x}), l(\overline{x}))}\right] \tag{20}$$

We conclude that 20 is positive since the city-wide average expected suppression cost (τ) falls between the minimum and maximium expected suppression cost: $\lambda \Pi^c l(0)c' < \tau < \lambda \Pi^c l(\overline{x})c'$. This implies that both $\frac{\partial \tau}{\partial \delta}$ and $\frac{\partial \overline{x}}{\partial \delta}$ are positive and that $\frac{\partial u}{\partial \delta}$ is negative.

□

First, note that in the absence of fire suppression externalities (i.e. if we were to set $\frac{d\Pi^c}{dc} \equiv 0$), the optimal choice of fire suppression is c^*, both for the individual and for the city as a whole. Then, this proposition implies that public provision of c^* will increase sprawl and make everyone worse off than private provision.

Unlike the welfare-improving sprawl from the previous section, the movement away from the city center in this context is a result of the government policy that underprices land in high risk areas since residents do not pay the full cost of protecting their homes from fire. This sprawl is associated with a decrease in welfare due to increasing fire suppression costs which are paid collectively by everyone in the city through higher taxes.

When there are fire suppression externalities, the welfare impact of an arbitrary level of public provision relative to private provision at c^* is ambiguous. This is because public provision can provide a benefit by correcting the externality but also has a drawback in that it lowers the costs of living in high risk low density locations. The net welfare impact of these two opposing effects depends on the chosen level of public suppression and may be positive or negative. Even if the net welfare impact of public provision relative to private provision is positive, the proposition also shows that public provision funded with an income tax will lead to more sprawl and lower welfare than would otherwise be possible with a private mandate.

In other words, even in the best case, public provision with an income tax is not the ideal way to provide fire suppression services.

5 A Risk-Based Tax

In this section, we continue with the “wildfire” model from the previous section in which fire risk is inversely related to urban density, but we modify the model so that the tax is location-dependent and based on fire risk. We show that a tax based on fire risk provides the benefits of public provision while eliminating the negative effects of funding through income taxation including excessive sprawl and higher suppression expenditures. This policy always leads to greater welfare among city residents than private provision or public provision with an income tax.

With a risk-based tax, each resident pays the following tax which depends on their location in the city:

$$\tau(x) = \lambda\Pi(c^g, l(x))c^g = \lambda\Pi^g l(x)c^g \tag{21}$$

where $\Pi^g = \Pi^c(c^g)$. Replacing Equation 1 with Equation 21 and substituting Equation 21 into Equation 3 yields a new utility maximization problem:

$$max_l U(y - tx - rl - \delta\lambda\Pi^g l(c^g + \hat{S}(c^g)) - (1-\delta)\lambda\Pi^p l(c^p + \hat{S}(c^p)), l). \tag{22}$$

where $\Pi^p = \Pi^c(c^p)$. This does not effect our previous results in Equations 6 or 7. However, we now get the following result for $\frac{\partial r}{\partial \delta}$:

$$\frac{\partial r}{\partial \delta} = \lambda\Pi^p(c^p + \hat{S}(c^p)) - \lambda\Pi^g(c^g + \hat{S}(c^g)) \tag{23}$$

Let $\Psi(c)$ denote the expected cost of fire per unit of land as a function of c:

$$\Psi(c) = \lambda \Pi^c(c)(c + \hat{S}(c)) \tag{24}$$

Public provision with the risk-based tax makes everyone in the city better off compared to private provision, as shown in the following proposition.

Proposition 5.1. *If public provision is funded with a risk-based tax as in Equation 21,* $\forall c^g \in [0, \overline{c}]$*, the following two statements are true if and only if* $\Psi(c^g) < \Psi(c^*)$*:*

1. *all residents of the city are better off with public provision of* c^g *than with private provision, and*

2. *the city is spatially larger with public provision of* c^g *than with private provision.*

Proof. Since we are comparing private provision without a mandate, we let $c^p = c^*$ and note that $\frac{\partial r}{\partial \delta} = \Psi(c^*) - \Psi(c^g) > 0$ if the condition in the proposition is met.

Noting that $\frac{\partial r}{\partial x} = \frac{-t}{l}$, Equation 11 can be written as

$$tn = -\int_0^{\overline{x}} \frac{\partial r}{\partial x} dx = r(0) - r(\overline{x}) \tag{25}$$

Applying Equation 10 yields

$$tn = -\int_0^{\overline{x}} \frac{\partial r}{\partial x} dx = r(0) - r^a \tag{26}$$

Totally differentiating with respect to δ yields

$$0 = \frac{\partial r(0)}{\partial \delta} + \frac{\partial r(0)}{\partial u} \frac{\partial u}{\partial \delta} \tag{27}$$

or

$$\frac{\partial u}{\partial \delta} = -\frac{\frac{\partial r(0)}{\partial \delta}}{\frac{\partial r(0)}{\partial u}} \tag{28}$$

From Equation 7, we know that $\frac{\partial r(0)}{\partial u} < 0$. Since $\frac{\partial r}{\partial \delta} > 0$, $\frac{\partial u}{\partial \delta} > 0$. This shows that residents are better off with public provision when $\Psi(c^g) < \Psi(c^*)$. Noting that $\frac{\partial r}{\partial \delta} \leq 0$ when this condition is not met, it is clear that $\frac{\partial u}{\partial \delta} > 0$ only when $\Psi(c^g) < \Psi(c^*)$.

Totally differentiating Equation 10 with respect to δ yields

$$\frac{\partial r(\overline{x})}{\partial \delta} + \frac{\partial r(\overline{x})}{\partial u}\frac{\partial u}{\partial \delta} + \frac{\partial r(\overline{x})}{\partial x}\frac{\partial \overline{x}}{\partial \delta} = 0 \tag{29}$$

Rearranging and substituting Equation 28,

$$\frac{\partial r(0)}{\partial u}\frac{\partial r(\overline{x})}{\partial x}\frac{\partial \overline{x}}{\partial \delta} = \frac{\partial r(\overline{x})}{\partial u}\frac{\partial r(0)}{\partial \delta} - \frac{\partial r(\overline{x})}{\partial \delta}\frac{\partial r(0)}{\partial u} \tag{30}$$

Since $\frac{\partial r(0)}{\partial u} < 0$ and $\frac{\partial r(\overline{x})}{\partial x} < 0$, $\frac{\partial \overline{x}}{\partial \delta}$ has the same sign as

$$\frac{\partial r(\overline{x})}{\partial u}\frac{\partial r(0)}{\partial \delta} - \frac{\partial r(\overline{x})}{\partial \delta}\frac{\partial r(0)}{\partial u} \tag{31}$$

Substituting Equations 7 and 23 , 31 becomes

$$\left(\lambda\Pi^p(c^p + \hat{S}(c^p)) - \lambda\Pi^g(c^g + \hat{S}(c^g))\right)\left(\frac{1}{l(0)U_1(z(0), l(0))} - \frac{1}{l(\overline{x})U_1(z(\overline{x}), l(\overline{x}))}\right) \tag{32}$$

Since $\frac{dU_1(z(x),l(x))}{dx} > 0$ and $\frac{\partial l}{\partial x} > 0$, the second term in 32 is positive and $\frac{\partial \overline{x}}{\partial \delta}$ has the same sign as $\frac{\partial r}{\partial \delta}$, positive if and only if $\Psi(c^g) < \Psi(c^*)$.

□

It is also evident that public provision with a risk-based tax makes residents better off than with an income tax.

Proposition 5.2. $\forall c' \in [0, \overline{c}]$, *public provision of* c' *funded with a risk-based tax, compared to public provision of* c' *funded with an income tax:*

1. *all residents of the city are better off with the risk-based tax than the income tax, and*

2. *the city is spatially larger with the income tax compared to the risk-based tax.*

Proof. Note that the risk-based tax for c' is equivalent to a private mandate of c' from the perspective of a consumer's optimization problem. Having already showed in Proposition 4.2 that the mandate leads to higher welfare and a smaller city than public provision with an income tax, the same results extend to a risk-based tax in comparison to an income tax. □

These two propositions demonstrate that residents are better off with public provision with a risk-based tax than with either private provision or public provision with income taxation. Furthermore, the risk-based tax leads to some sprawl but less sprawl than income taxation. The reduction in fire risk relative to private provision provides greater income to residents which causes the city to expand even with a risk-based tax. However, the amount of sprawl will be less than with an income tax because all residents pay the true expected cost of provision for their location, and this sprawl is welfare-improving sprawl, not the result of poor incentives.

6 Policy Implications

The previous section has shown that differentiated taxes based on fire risk accomplish the goal of internalizing fire suppression externalities without leading to excessive urban sprawl and lower welfare of residents. Recent advances in assessing wildfire risk at a detailed level make taxes like this feasible. In this section, we conclude with some alteranative solutions that require less information to implement or that may be politically easier to enact.

One alternative is for fire suppression agencies to charge a fee for services following successful defense of a structure instead of funding services through taxation. Like a risk-based tax, residents' expected suppression expenses reflect the true cost of suppression at each location. With appropriate choice of c by fire suppression agencies, this policy will also make residents better off than with income taxation or private provision. Note, however, that for risk averse agents (unlike the risk neutral agents in our model), it would be preferable to pay a certain tax based on expected suppression costs than to pay the actual cost of suppression. The actual cost of suppression is likely to be small in many years and catastrophically large when a fire occurs. Risk averse residents will prefer the fair insurance provided by the risk-based tax relative to the fee-for-services approach. This highlights another benefit of public provision funded through taxes in addition to the correction of fire suppression externalities: public provision serves to pool risk related to uncertain and variable fire suppression costs.

An alternative to the annual risk-based tax proposed in the previous section is a fire suppression impact fee at the time of development in the WUI. This impact fee should be set as the present value of the stream of risk-based tax payments, or equivalently, as the present value of expected fire suppression costs at that location. If fire risk and other parameters are not changing over time, then this approach is equivalent to the annual risk-based tax. Like the annual tax, this will discourage development in low density high risk locations at the urban fringe, thereby reducing sprawl and lowering expected annual fire suppression costs.

Non-market solutions to this problem include imposing regulation on growth and development in the WUI to prevent development in high risk areas and lower expected suppression costs. Another possibility is a re-prioritization of fire suppression activities away from private goods like structure defense and toward public goods like defense of critical infrastructure and densely populated urban areas. Under this approach, fire suppression agencies would let structures burn if their defense does not provide benefits in containing the larger fire (and assuming residents have already been evacuated). This would prevent situations where agencies spend more defending a structure than the replacement value of the structure. It would also increase the cost to residents in the WUI who can no longer count on publicly provided suppression in the event of a fire. Similar to the risk-based tax, this should reduce development in the WUI relative to public provision with income taxation.

The primary conclusion of this paper is that the widespread growth and development in the wildland urban interface and the resulting increase in fire damage and fire suppression expenditures is partly a result of underpriced fire protection for those in the interface relative to those in traditional urban areas. To address this problem, policy makers should consider new approaches to funding fire suppression activities. Risk-based taxes will lead to less sprawl, lower expected fire suppression expenditures, and higher welfare relative to the prevalent ways of funding fire suppression agencies today.

Another implication of our model is that the public provision of $\bar{c}$, the maximum technologically possible fire suppression level, is not necessarily optimal and may be worse than private provision. This appears to be the strategy used by many fire suppression agencies, to use any and all resources to contain any fire (Ingalsbee, 2000). It is important for suppression agencies to weigh the benefits of suppression (saved structures) against the cost, not to simply minimize damages.

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